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Z' Bosons and Supersymmetry[1]

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Abstract

A broad class of supersymmetric extensions of the standard model predict a Z' vector boson whose mass is *naturally* in the range 250 GeV$<M_{Z'}<$2 TeV. To avoid unacceptably large mixing with the Z, one requires either a discrete tuning of the $U(1)'$ charges or a leptophobic Z'. Both cases are likely to arise as the low energy limits of heterotic string compactifications, but a survey of existing realistic string models provides no acceptable examples. A broken $U(1)'$ leads to additional D-term contributions to squark, slepton, and Higgs masses, which depend on the $U(1)'$ charge assignments and the Z' mass. The Tevatron and future colliders can discover or decisively rule out this class of models.

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1 Introduction

The minimal extension of the standard model (SM) gauge group is to append an abelian factor $U(1)'$. If at least some of the SM particles have nonzero $U(1)'$ charges, the $U(1)'$ gauge symmetry must be spontaneously or dynamically broken at some scale greater than the weak scale, leading to a massive Z' vector boson which decays into SM particles and mixes with the SM Z boson. The existence of such broken $U(1)'$ gauge symmetries is a natural prediction of grand unification schemes like $SO(10)$ and E_6, as well as superstring theory.

It is important to distinguish between models in which the mechanism of $U(1)'$ breaking is linked to the mechanism of electroweak symmetry breaking (EWSB), and models in which the mechanism of $U(1)'$ breaking is independent of, or merely parallels, that of EWSB. An example of the first case is a technicolor theory with a $U(1)$ factor in the technicolor gauge group. Here obviously the Z' mass is tied to the technicolor scale and thus to the electroweak scale. Although a technicolor $U(1)'$ has no tree level couplings to SM particles, it is in principle observable due to loop or strong interaction effects [1]. An example of the second case is a grand unified (GUT) theory in which $U(1)'$ breaking is triggered by the renormalization group (RG) evolution of (exotic) Yukawa couplings driving some (exotic) scalar mass squared negative. Here the mechanism of $U(1)'$ breaking parallels a possible mechanism of EWSB, but due to the logarithmic nature of the RG evolution, the Z' mass is highly unlikely to be within 1 or 2 orders of magnitude of the Z mass without considerable tuning of the model. Indeed generically $M_{Z'}$ lies in the range 10^8 to 10^{16} GeV for GUT models.

In this regard, it is interesting to examine the status of Z' bosons in models of *weak-scale supersymmetry*. This is the class of models which embed the supersymmetrized standard model and tie EWSB to supersymmetry breaking (usually via the dynamics of some new "messenger" fields). This includes the minimal supergravity models [2] (also called CSSM, MLES, and occasionally (improperly) MSSM), as well as the gauge-mediated low energy breaking models (GMLESB) [3]. In weak-scale supersymmetry the effective supersymmetry (SUSY) breaking scale in the "visible" sector is the same as the weak scale, $m_{\rm EW} = 246$ GeV. Typically the up and down-type Higgs, the squarks, sleptons, and gauginos all get soft SUSY breaking mass terms which are of order $m^2_{\rm EW}$.

In workable models [4] EWSB occurs radiatively, i.e., the up-type Higgs mass squared is driven negative in the RG evolution, due to the large top quark Yukawa. In weak scale supersymmetry models with a Z' it is typical that the $U(1)'$ breaking is also radiative, i.e. it is triggered either by a scalar mass squared going negative or condensate formation, both mechanisms being driven by RG evolution. Cvetic and Langacker [5] have identified the subset of models for which the Z' is naturally light – within an order of magnitude of the weak scale. This subset of weak scale supersymmetry models is the subject of this report. One should note, however, that in SUSY models even a very heavy Z' does not always completely decouple from collider physics, because the $U(1)'$ breaking induces D-term contributions to scalar masses.

Direct production of a Z', followed by decay to electrons, muons, or jets, will be observable at the LHC for $M_{Z'} \leq$ about 5 TeV, assuming roughly SM strength couplings [6, 7]. The most stringent current bounds come from the CDF (preliminary) analysis of $Z' \to ee$, $\mu\mu$ in 110pb^{-1} of Tevatron collider data [8]. Assuming SM couplings to leptons produces the bound $M_{Z'} > 690$ GeV. For a "leptophobic" Z', a mass bound is obtained from the dijet channel, i.e. searching for resonant structure in the dijet invariant mass spectrum, assuming that the Z' width is not too large. The current limit from UA2 for SM couplings is [9] $M_{Z'} > 237$ GeV; a CDF dijet analysis [10] excludes Z' bosons over a wide mass range up to about 1 TeV, but only for couplings which are considerably more than SM strength[3]. Besides direct production, Z-Z' mixing implies effects on the oblique parameters S,T, and U, as well as other precision electroweak observables [1]. The current LEP data provides strong constraints on these effects; depending on the Z' couplings to SM fermions, one can rule out $M_{Z'}$ as large as 400 GeV, and Z-Z' mixing angles greater than a few times 10^{-3} [5].

2 Supersymmetry and $U(1)'$ Breaking

The $U(1)'$ gauge symmetry is broken by nonzero vevs of the scalar components of some chiral superfields which have nonzero $U(1)'$ charge. These chiral superfields may represent either fundamental particles or composites (or both). Since we are only interested in $U(1)'$ breaking in the visible sector, this vacuum state must be continuously connected to a SUSY-preserving

[3]The CDF data do not extend the UA2 bound for SM strength couplings essentially because of extensive prescaling for dijet masses below 353 GeV.

vacuum, reached in the limit that the soft SUSY breaking terms are turned off. Thus we may always assume that the $U(1)'$ breaking vacuum lies in some F and D flat direction, modulo corrections of order the soft breaking scale, m_{soft}.

Since the scalars which get vevs carry (at least) a nonzero $U(1)'$ charge, D flatness implies that there are at least two fields which get vevs, modulo [4] corrections of order m_{soft}. At least one of these fields must be a SM singlet, since the scenario in which $U(1)'$ is broken just by the supersymmetric SM Higgs H_U and H_D is phenomenologically untenable. There are thus two classes of models to consider:

- Models with two or more SM singlets getting $U(1)'$ breaking vevs.
- Models with a single SM singlet, S, getting a $U(1)'$ breaking vev. In these models D flatness requires one or both of the SM Higgs H_U and H_D has a nonzero $U(1)'$ charge.

In the first case, D flatness imposes a relation between the SM singlet vevs, but does not fix the overall scale. Instead, $M_{Z'}$ is determined by the RG evolution which (by assumption) drives the singlet mass squareds negative, together with the corrections to D-flatness of order m_{soft}.

In the second class of models, D flatness implies that the vev of S is related to the Higgs vevs (with coefficients that are just the $U(1)'$ charges), modulo corrections of order m_{soft}. Let us suppose that the soft breaking mass m_S associated with S is of order the weak scale. This will in fact be true automatically in most models, since the SM soft breaking terms are of order m_{EW}. For this subset of weak scale supersymmetry models it is clear that the vev of S is of order m_{EW}, since

$$m_S \simeq m_{\mathrm{soft}} \simeq m_{\mathrm{EW}}. \tag{1}$$

The resulting value of $M_{Z'}$ is a function of gauge couplings and the parameters

$$m_S, m_{\mathrm{EW}}, Q'_S, Q'_H, \tag{2}$$

[4]Note that "modulo" includes the possibility that only one scalar gets a $U(1)'$ breaking vev, as long as this vev is no larger than order m_{soft}, and vanishes when the soft breaking is turned off.

where the latter two are the $U(1)'$ charges of S and the Higgs doublet(s). $M_{Z'}$ is naturally within an order of magnitude of $m_{\rm EW}$ in this class of models, which I will refer to as "Cvetic-Langacker" models.

Since we have assumed that S gets a vev, the RG evolution must drive m_S^2 negative at some scale Λ. This does not imply, however, that Λ is anywhere near $m_{\rm EW}$; it may be many orders of magnitude larger. Nevertheless supersymmetry ensures that the vev of S is of order $m_{\rm EW}$, not of order Λ.

As emphasized by Cvetic and Langacker [5], the main phenomenological deficiency of this class of models is that the Z-Z' mixing angle is not sufficiently suppressed for $M_{Z'} \simeq 1$ TeV. This problem is avoided in two cases:

- The Z' is leptophobic, i.e. the Q' charges of the SM leptons vanish.
- Q'_S and Q'_H have the same relative sign and take values in a certain narrow range.

Either case can be considered a discrete tuning of the $U(1)'$ charges. Thus although the above discussion relied only on general properties of weak scale supersymmetry, to get a completely natural scenario we must embed these models in a larger framework like GUT's or superstrings.

3 Superstring Models

For purposes of studying phenomenological prospects at future colliders, it would be useful to have one or more "benchmark" models with naturally light Z''s. Because of the Z-Z' mixing problem, an obvious place to look is among the known four-dimensional N=1 spacetime supersymmetric solutions to the weakly coupled heterotic superstring.

Roughly two dozen heterotic string vacua have been constructed which are realistic in the sense that they embed the SM gauge group along with three generations of SM fermions and some number of vectorlike exotics. These string models often contain one or more $U(1)'$'s which remain unbroken at the string scale, and a number of SM singlet fields which have nonzero charges under $U(1)'$. The $U(1)'$ charges of all particles, including SM particles, are fixed. Each string model is actually a continuous multiparameter family of string vacua, depending on the values of moduli vevs which are not determined in string perturbation theory. Further, although these string

Model	Leptophobic $U(1)'$?	$Q'_H \neq 0$?
Faraggi I [13]	no	–
Faraggi II [14]	yes	no
Faraggi et al [15]	no	–
Chaudhuri et al [16]	yes	no
Hockney-Lykken [17]	yes	no
Flipped SU(5) [18]	yes	yes

Table 1: Partial survey of string models for leptophobic Cvetic-Langacker candidates.

models contain roughly the right ingredients for hidden sector dynamical SUSY breaking, no one has as yet performed a detailed analysis of SUSY breaking and the resulting soft breaking terms for a complete realistic string model. Nevertheless given the fixed $U(1)'$ charges and using various string consistency conditions, one can determine whether the Cvetic-Langacker scenario is at least possible in a given string model.

Cvetic and Langacker surveyed some existing string models for cases which employ the second, leptophilic, solution of the mixing problem. They found no acceptable candidates. This is not surprising given that only a handful of models were looked at, and that this solution requires a a tuning of Q'_S and Q'_H.

I have performed a similar survey of half a dozen string models, this time looking for Cvetic-Langacker in the leptophobic mode. The results are shown in Table 1.

This sampling of models is sufficient to draw two major conclusions:

- It is not difficult to construct realistic string models with a leptophobic $U(1)'$ unbroken at the string scale. This observation has already been made in the literature [11, 12].

- The leptophobic string models are unlikely to be Cvetic-Langacker models, because typically the Higgs doublets are uncharged under the leptophobic $U(1)'$. The exception to this rule in Table 1 is the flipped $SU(5)$ model. The reason for this is rather elementary: the existing realistic string models have an underlying E_6, $SO(10)$, or $SU(5)$ gauge structure built in, broken in a stringy way by Wilson lines. In order to have nonvanishing Yukawa couplings, the Higgs doublets typically have nonvanishing charge only under these E_6 based $U(1)$s (in the simplest models, the Higgs arise from the untwisted sector). It is well known that within E_6 the only possibility for symmetry-based leptophobia is flipped $SU(5)$[5].

Unfortunately flipped $SU(5)$ does not provide an acceptable example of a Cvetic-Langacker model either. Having fixed the particle identification in the usual way so as to generate a large top quark Yukawa, one finds that the first and second generation quarks have different charges under the leptophobic $U(1)'$. This would lead to flavor-changing neutral currents[6].

4 D-Term Contributions to Scalar Masses

As mentioned in the introduction, even a very heavy Z' boson does not completely decouple from collider physics in a supersymmetric theory [22]. This is because a D-term contribution is generated to the scalar potential:

$$V_D = \frac{g^2}{2}\left[\sum_i Q_i|\phi_i|^2\right]^2 , \tag{3}$$

where g is the $U(1)'$ gauge coupling, ϕ_i are all the scalar fields, and Q_i are their $U(1)'$ charges. Since some of the scalars must get vevs to break the

[5] If there is Z-Z' or photon-Z' mixing in the kinetic terms of the effective field theory, then leptophobia is still possible within E_6 [19, 20, 21]. This involves subtle issues regarding the effective gauge kinetic function which are beyond the scope of this report.

[6] This is not necessarily a disaster if the Z' charge eigenstate down-type quarks are also mass eigenstates: see the revised version of [12].

$U(1)'$, every scalar mass squared receives a contribution of the form [23]

$$\Delta m_i^2 = Q_i \Lambda^2, \tag{4}$$

where Λ is an overall scale[7].

In the Cvetic-Langacker scenario these D-term contributions are given by the approximate expression:

$$\Delta m_i^2 = Q_i \frac{M_{Z'}^2}{2Q_S}. \tag{5}$$

These splittings are roughly of order $\pm(250\ \mathrm{GeV})^2$. Thus if supersymmetry is observed in future collider experiments, a Cvetic-Langacker Z' implies large deviations in the sparticle mass spectrum from the patterns characteristic either of minimal supergravity or of GMLESB.

5 Conclusion

Within the context of weak scale supersymmetry there is a broad class of models which predict a Z' boson whose mass cannot be much more than 1 TeV. This prediction is natural given the usual assumptions of weak scale supersymmetry. To achieve in addition a large natural suppression of Z-Z' mixing, these models should be embedded in some larger framework such as superstrings. There are some obstacles to providing acceptable superstring models, but they do not seem insurmountable. A "benchmark" model, i.e. a specific realization of the Cvetic-Langacker scenario with fixed $U(1)'$ charge assignments, has at most one new free parameter compared to minimal supergravity or whatever version of weak scale SUSY it is embedded in. However such a model has many new observables: the Z' mass, width, and branching fractions to SM and sparticle decay modes, as well as the observable effects of Z-Z' mixing. These observables can be used to provide overconstrained predictions of the D-term contributions to scalar masses.

If these models are realized in the leptophobic mode, the Z' resonance must still show up in the dijet spectrum at either the Tevatron or the LHC. A SUSY Z' discovery would be strong motivation towards running a high

[7]It may appear that the D-terms also imply new contributions to the quartic scalar couplings; that this is false can be seen by explicitly integrating out the fields whose vevs break $U(1)'$.

luminosity NLC at the Z pole, and towards building a muon collider which could operate at the Z' pole.

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